

Tri-gas Thruster Analysis

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Abstract

The purpose of this project was to explore the practicality and performance of a small Tri-gas thruster for in-space propulsion. Thrust is created in this type of system by passing propellant through a densely packed catalyst bed. The propellant, a stoichiometric mixture of hydrogen and oxygen combined with nitrogen, was specifically created for this application. A complex network of valves, regulators, transducers, and K-Bottles was utilized in creating this gas. Another system was designed and built for testing the thruster using this propellant. For evaluation of performance certain parameters were varied. These include catalyst type, catalyst bed length, start-up temperature, and inlet pressure. Testing confirms that a Tri-Gas thruster achieved a higher I_{sp} than a nitrogen cold gas thruster. A higher startup temperature leads to a lower time to reach steady state temperature. During the latter part of the testing, a decrease in thruster performance was observed. The reason behind this decrease is currently unknown

Nomenclature

I_{sp} = Specific impulse, s	c^* = Characteristic velocity, ft/s	g = Acceleration due to gravity, ft/s ²
γ = Ratio of specific heats, unitless	p_e = Exit pressure, psia	p_c = Chamber pressure, psia
F = Thrust, lbf	V = Velocity (ft/s)	GO_x = Gaseous oxygen
GN_2 = Gaseous nitrogen	GH_2 = Gaseous hydrogen	Q = Heat energy, BTU
ΔT = Temperature change, F or R	C_p = Isobaric specific heat, BTU/lbm-F	m = Mass, lbm
a = Sonic velocity, ft/s	T = Temperature in Rankine	T_0 = Stagnation temperature, R
A_t = Throat area, ft ²	T_F = Temperature in Fahrenheit	p_a = Ambient pressure, psia
A_e = Exit area, ft ²	M_e = Exit Mach number	R_{sub} = Thermal resistance

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= Inner convection coefficient, Btu/(s-ft ² -R)	= Inner surface area, ft ²	r = radius, ft
= catalyst bed length, ft	= Macor thermal conductivity, Btu/(s-ft-R)	= Steel thermal conductivity, Btu/(s-ft-R)
= Outer surface area, ft ²	Re = Reynolds number	
= Prandtl number	= Nusselt number based on thruster outer diameter	= Rayleigh number based on thruster outer diameter
= Fluid temperature, R	= Ambient temperature, R	= Fluid volume flow rate, ft ³ /s
= Fluid mass flow rate, lbm/s	= Fluid density, lbm/ft ³	= Fluid viscosity, lbm/ft-s
= Mass velocity, lbm/ft ² -s	= Conversion factor, 144 in ² /ft ²	= Particle diameter, ft
= Nusselt number based on particle diameter	= Tube friction factor	= Tube diameter, ft
AFRL = Air Force Research Lab	MSFC = Marshall Space Flight Center	

I. Introduction

Performance, reliability, cost, complexity, and weight are extremely important parameters when considering the design of an in-space propulsion system. Satellites require attitude control systems that will work both on a continuous basis and intermittently. However a simple, reliable system often has lackluster performance. An example of a simple thruster currently used for attitude control is a cold gas thruster. An inert gas is pushed through a nozzle and produces thrust. It has a short thrust rise time and involves very few components. If it was not for the extremely low specific impulse (I_{sp}) this would be an ideal system.

A Tri-gas thruster employs a similarly simple design while improving performance. By passing an inert Tri-gas through a catalyst bed, a larger I_{sp} can be obtained while keeping the overall design relatively simple. There is still only one tank of gas and one valve, but as the gas is hotter the specific impulse is higher. By designing and testing a 5lb Tri-gas thruster in various configurations, the optimum thruster design can be found and implemented in space applications.

II. Tri-gas Thrusters vs. Cold Gas

Thrusters

Cold gas thrusters have historically been used for satellite attitude control. They are chosen for their high reliability, safe operability, and low complexity. Typically an inert gas is stored in a high pressure tank. A pressure regulator is included in the system to maintain a constant chamber pressure, which will effectively supply the spacecraft with steady thrust. Cold gas thrusters are simple systems, but consequently have a low specific impulse.

Tri-gas thrusters were created as an alternative to cold gas thrusters. Their development was based upon increasing specific impulse while sustaining

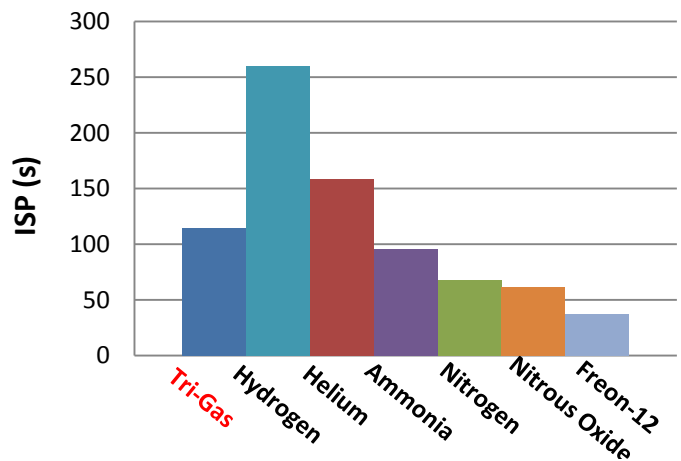


Figure 1: Theoretical ISP of Tri-gas vs. Candidate Cold Gases in a Vacuum

overall system simplicity. Tri-gas gas is a stoichiometric mixture of oxygen and hydrogen, diluted with nitrogen until it is inert. Similar to cold gas thrusters, Tri-gas is stored in a high pressure tank and expanded out of a nozzle. However, before entering the throat of the nozzle, the Tri-gas gas passes through a catalyst bed. The catalyst bed will react the oxygen and hydrogen, raising the exiting gas temperature. Tri-gas thrusters have higher specific impulse over other cold gas thrusters due to the increase in exiting gas temperature. The benefit of Tri-gas thrusters can be seen in Figure 1.

The I_{sp} of Tri-gas thrusters can be predicted utilizing the same equations as cold gas thrusters. The following equation is eq. 3.197 from Space Propulsion Analysis and Design.

$$I_{sp} = \frac{1}{g_0} \sqrt{\frac{2 \gamma}{\gamma - 1} \frac{P_c}{\rho_c}} \left(\frac{P_c}{P_a} \right)^{\frac{1}{\gamma}} \left(\frac{P_a}{P_c} \right)^{\frac{\gamma}{\gamma - 1}} \quad \text{Equation 1}$$

(Ref. 1)

The above equation calculates the theoretical I_{sp} , which is derived from the properties of the exiting gas. To appropriately apply this equation towards Tri-gas thrusters, two main assumptions must be made: the exiting gas maintains the initial content of nitrogen, while all of the oxygen and hydrogen are converted to water; secondly, the working gas, before it travels through the throat, is at the adiabatic flame temperature of the H_2 / O_2 reaction. Figure 2: Theoretical ISP vs. Exhaust Temperature at Sea-Level for an Exit Gas Composition of 94.667% N_2 and 5.333% H_2O shows I_{sp} vs. Gas Temperature for Tri-gas gas. The maximum theoretical I_{sp} for a 92% nitrogen Tri-gas thruster at sea-level is highlighted with the red triangle.

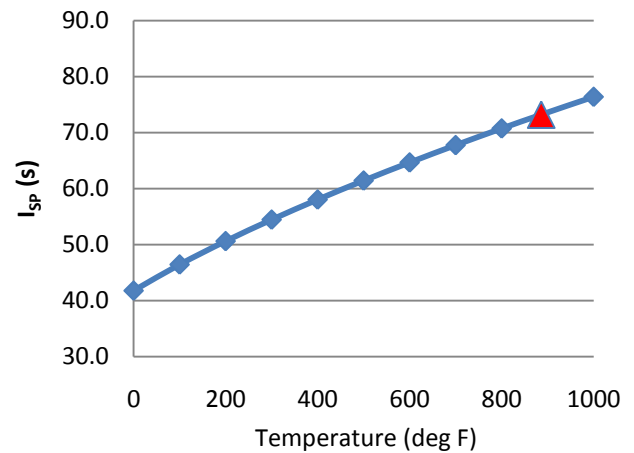


Figure 2: Theoretical ISP vs. Exhaust Temperature at Sea-Level for an Exit Gas Composition of 94.667% N_2 and 5.333% H_2O

III. Creating Tri-gas

In order to control every aspect of the Tri-gas thruster testing, propellant creation was included in the project. While Tri-gas can be bought, the ability to create any variation of nitrogen, oxygen and hydrogen increased testing potential.

A. Tri-gas Mixing

As one of the advantages of using Tri-gas in an attitude control thruster is its inertness, previous Tri-gas testing was studied to determine at what point the Tri-gas became flammable. Figure 3 shows the results of the literature search. The limit of stoichiometric hydrogen/oxygen according to the NSS report is approximately 88% by volume nitrogen, 8% by volume hydrogen, and 4% by volume oxygen. To stay well outside of this limit, the Tri-gas created for this project was 92% by volume nitrogen, 5.33% hydrogen, and 2.67% oxygen. To further support the assumption that 92% nitrogen is inert, a study at AFRL showed no ignition when nitrogen was over 80% (Ref. 3). This can be seen in Table 1.

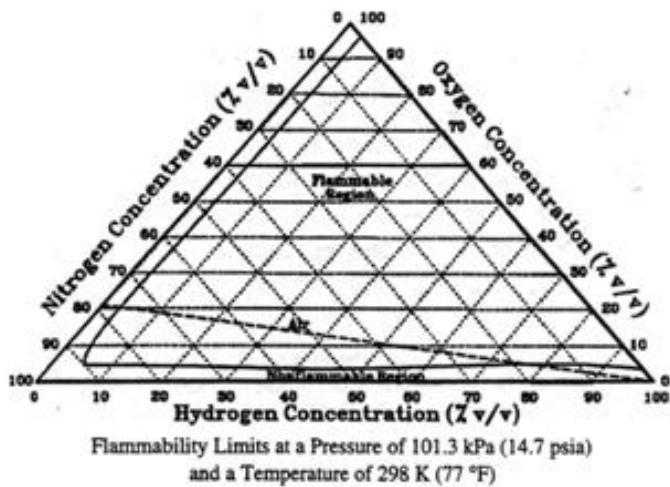


Figure 3: Flammability Limits of Tri-gas

(Ref. 1)

B. Creation Rig

In order to provide a capability that will allow different gas percentages of the Tri-gas mixture, it was necessary to design and build a gas distribution system that could combine the different gases into a single storage bottle and allow for the different gases to be added into the bottle in a safe manner. Such a system was designed and built for the purpose of creating custom Tri-gas mixtures to observe the effects on performance. The final system design can be seen in Figure 4 and includes several hand valves, check valves, filters, pressure regulators, an orifice, pressure gauges, and a pressure transducer that are all integrated with 1/4" x .049" tubing.

All of the components were sized to have a large safety factor over the 2200 psig maximum pressure of the system and to have an acceptable pressure drop. The orifice was sized to limit the mass flow to a rate that is below the maximum mass flow rate of the relief valve. This was done to make sure that the system will be able to decompress if the relief valve is opened.

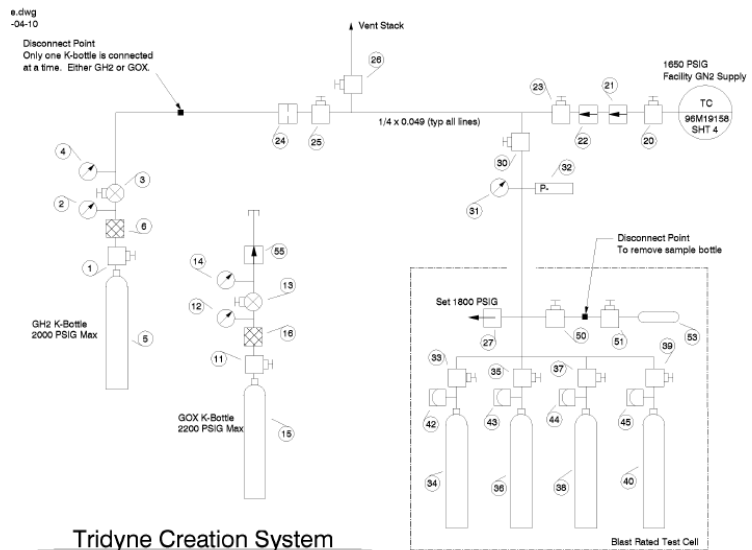


Figure 4

C. Procedure

To safely create Tri-gas, a strict procedure was written to account for the correct concentrations of hydrogen, oxygen and nitrogen. The method used was that of partial pressures. To begin, the system was purged with nitrogen 3 times. Then the bottle was loaded with 200 psig of nitrogen. The pressure was allowed to settle for several minutes before it was increased to 240 psig with oxygen. Oxygen was the first reactive gas added to system to avoid high pressure oxygen flowing through the lines. Once oxygen was loaded in the Tri-gas K-bottle, the GOx bottle was replaced with the H₂ bottle and the lines were purged with nitrogen. The K-bottle was then charged to 1419

Run	Environmental Temperature, F	Propellant Concentrations, volume percent				Theoretical Incremental Temperature, F	Comments
		O ₂	H ₂	CH ₄	Inert		
1	75	5.6	7.2		89.2 (He)	1473	No ignition
2	75	5.4	10.7		83.9 (He)	2180	No ignition
3	75	7.15	14.3		78.6 (He)	2920	No ignition
4	75	8.95	17.9		73.2 (He)	3650	No ignition
5	75	10.7	21.4		67.9 (He)	4370	Ignition
6	200	5.4	10.7		83.9 (He)	2180	No ignition
7	200	6.25	12.5		81.8 (He)	2550	No ignition
8	200	7.15	14.3		78.6 (He)	2920	Ignited after ~2-second delay
9	260	8.95	17.9		73.2 (He)	3659	Ignition
10	75	15.0	30.0		55.0 (N ₂)	427*	Ignition
11	75	10.0	20.0		70.0 (N ₂)	2850	Ignition
12	75	8.75	17.5		73.75 (N ₂)	2500	Ignition
13	75	7.5	15.0		77.5 (N ₂)	2150	No ignition
14	75	8.2	16.4		75.4 (N ₂)	2320	No ignition
15	200	6.25	12.5		81.25 (N ₂)	1440	No ignition
16	200	7.5	15.0		77.5 (N ₂)	1720	No ignition
17	200	8.0	16.0		76.0 (N ₂)	1850	No ignition
18	200	8.75	17.5		73.75 (N ₂)	2500	Ignition

Note: All runs made at 2000 psia.

Table 1: Summary of Deflagration/Detonation Tri-gas Test Results

psig with nitrogen. The final gas, hydrogen, was added to the K-bottle until the pressure read 1500 psig. A sample bottle was taken to be tested for composition.

During Tri-gas fill problems arose as the K-bottle pressure increase caused a similar temperature increase. The variations in temperature caused the pressure to swing wildly. To control this problem, the K-bottles were water cooled during fill. This increased temperature stability and pressure accuracy.

D. Safety Concerns

To insure personnel safety, an in-depth safety analysis was conducted. Five potential hazards were identified, and appropriate actions were taken to mitigate their presence.

The first danger identified was an overpressure of the vessels in which Tri-gas is created, potentially rupturing and fragmenting the container. This risk was reduced by using suitable DOT certified K-bottles. Furthermore, the upstream relief valve was set for a pressure below that of the sample bottle pressure rating.

The tubing system for the GN_2 , GOx , and GH_2 also could potentially fail. Tube rupture would cause facility damage and personnel injury. This concern was alleviated by verifying the pressure system was designed in accordance with ASME requirements. Additional safety precautions were taken by proof and leak testing lines after installation, and verifying pressure relief devices were installed to prevent pressure from rising above 110% of the maximum working pressure.

Beyond the concern of hardware failure, the gases being handled present a hazard of their own. Hydrogen is an extremely flammable element which could easily ignite or detonate. Creating a flammable or explosive mixture was avoided by purging the GH_2 transfer system. The transfer system was electrically grounded and all spark producing sources were at least 25 feet away. The GH_2 vent rate was limited to below 0.25 lbm/sec. The vent stack was located 15 feet above all local ignition sources.

Oxygen also presents challenges of its own. A fire or explosion due to an adiabatic compression or particle impact could cause ignition within the oxygen transfer system. This scenario was avoided by cleaning the oxygen system to MSFC Spec 164B-1A; valve components were certified for oxygen service. Filters were included in the system to remove particulates. The threat of extreme adiabatic compression was avoided by limiting fluid velocities to below 200 fps.

The last major concern with Tri-gas creation is a fire or explosion due to the hydrogen/oxygen/nitrogen mixture. Not producing a flammable combination was accomplished by regulating the pressure of the input gases. The error bounds on the target loading pressures were calculated to ensure a composition still within the non-flammable region of Tri-gas (Figure 3). To verify that a safe mixture was created a sample bottle of the mixed gas was sent to the MSFC Materials Lab for analysis.

IV. Tri-gas Thruster Design and Analysis

A. Thruster Design

To properly design the thruster, the properties of the gas used needed to be identified. From there, the nozzle and catalyst bed chamber wall could be sized and the materials chosen.

The properties of the gas that were of interest were the gas composition, specific heat ratio, and adiabatic flame temperature. The gas composition is controlled during the gas creation and the specific heat ratio is calculated using REFPROP for a specified temperature. Thus, the flame temperature is the only unknown left. This was calculated using a simple thermodynamic equilibrium that resulted in the maximum adiabatic gas temperature.

Equation 2

Equation 3

(Ref. 4)

Using the previously calculated values, the sonic velocity and c^* were calculated.

Equation 4

Equation 5

Once the gas properties were determined, the nozzle was sized by specifying a desired thrust level and combustion chamber pressure value.

Using these quantities, the area of the nozzle throat, the mass flow rate, and Mach number were calculated.

Equation 6

Equation 7

Equation 8

Using atmosphere as the exit pressure, to allow for close to perfect expansion at ambient conditions, the exit area of the nozzle was found.

Equation 9

(Ref. 1)

The final design of the thruster nozzle can be seen in Figure 5.

Once the nozzle dimensions were found, the catalyst bed chamber diameter was sized to a standard tube dimension that would provide ample area for the catalyst. To help the catalyst bed retain heat created during the reaction an insulative layer was put in the chamber. Several materials were considered, but the material that had both good thermal insulation properties and was easily machinable was Macor, a glass-ceramic material. The Macor was sized to be ¼" thick to provide ample insulation. Due to the experimental nature of the catalysts being used, a variable catalyst bed chamber length was chosen. This allowed the ability to experimentally find the optimal bed length with a single test thruster, which both cut down on cost and helped eliminate differences between bed length tests. The chamber was designed to accommodate a catalyst bed of 1" to 3" in length in ½" increments. These possible bed lengths were chosen based upon empirical data gathered from other thrusters of a similar design. To retain the catalyst inside the catalyst bed, screens were put into place above and below the bed. Both screens were of a wire mesh design that left approximately 50% of the cross-sectional area open. To provide structural support to the thin screens, a 0.048" thick perforated plate was placed below each screen. Each plate was left with 33% open area to allow for the Tri-gas to pass though somewhat uninhibited. To allow for the varying catalyst bed lengths, three Macor pieces

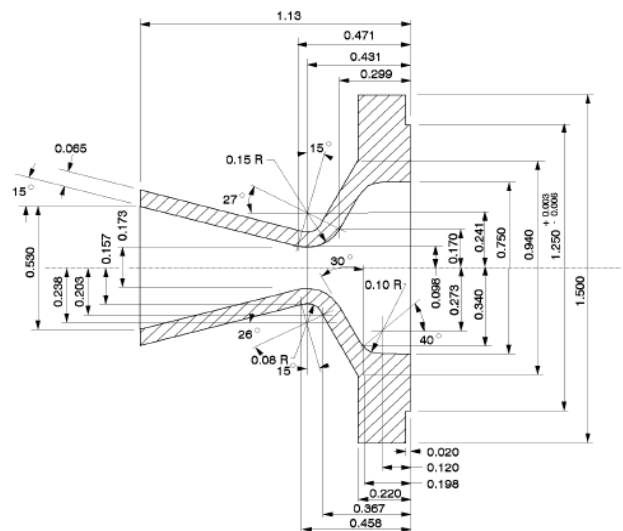


Figure 5: Nozzle Diagram

Technical drawing of a wellhead assembly, showing two views: a top view and a side view.

Top View Dimensions:

- Overall width: 4.25
- Mounting hole diameter: 0.325
- Distance between mounting holes: 1.320
- Overall length: 2.826
- Distance from edge to mounting hole center: 0.826
- Central opening diameter: 1.320
- Mounting hole diameter: 0.325
- Distance between mounting holes: 1.320
- Overall length: 2.826

Side View Dimensions:

- Overall height: 1.320
- Mounting hole diameter: 0.325
- Distance between mounting holes: 1.320
- Overall length: 2.826
- Distance from edge to mounting hole center: 0.826
- Central opening diameter: 1.320
- Mounting hole diameter: 0.325
- Distance between mounting holes: 1.320
- Overall length: 2.826

Labels:

- WELL HEAD
- WELL TUBE

To provide access to the catalyst bed and to allow for a flow path of the Tri-gas, an end flange needed to be designed for the thruster. The final design that was chosen incorporates two 5" flanges, one of which is welded to the catalyst bed chamber and the other incorporating a custom made gas diffuser and 1/2" female tubing port. The two flanges are mounted together using six 5/16" studs with nuts and washers. To ensure a high temperature leak proof seal between the flanges, each flange was machined with a 1/2" wide serrated concentric flange finish that seals with a graphite gasket.

0.90

0.50

0.20

Partially Flared End

0.125 dia thru
5 Slots equal spaced around circumference

After the thruster had been dimensioned the materials for its construction were selected based on availability, cost, and ability to handle the temperature and stresses that it will be subject to. These criteria led to the selection of ASTM A269 304 stainless steel seamless tubing for the catalyst bed chamber, A497 304 stainless steel for the nozzle material, and A479 304 stainless steel flanges.

A major goal of the Tri-gas testing is to evaluate ways of improving the thruster's response time. The system provides maximum I_{sp} and thrust when the catalyst bed is in thermal equilibrium with flowing Tri-gas. However, the catalyst bed takes a significant amount of time to reach steady state, limiting its appeal for attitude control.

C. Heat Transfer through the Catalyst Bed

The main problem with finding the heat transfer through the catalyst bed was determining the activity of the catalyst. Activity is the amount of catalyst that reacts per unit length. With the activity known, the amount of heat generated can be found, and the thermal network solved fairly easily. Without this number known, however, it is quite difficult (if not impossible) to determine the amount of heat generated.

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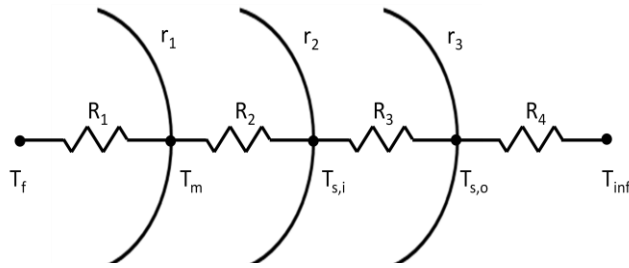


Figure 8: Thermal Resistance Network

thruster at the Macor interface, $T_{s,o}$ is the surface temperature of the steel thruster at the ambient interface and T_{inf} is the ambient temperature.

The thermal resistances of the radial network are also fairly simple. With k_m and k_s as the thermal conductivity values of the Macor and stainless steel, respectively, l as the differential length of the piece being considered, and h_i and h_o as the convection coefficients for the catalyst bed and ambient fluids, respectively, the thermal resistances turn out to be

Equation 10

Equation 11

Equation 12

Equation 13

(Ref. 4)

First examine these thermal resistances. R_1 requires the value of h_i to quantify it. Recall that this interior flow is flow through a catalyst bed. This can be modeled as a packed bed for heat transfer purposes. In *Handbook of Heat Transfer* (Ref. 4) a correlation is given for the particle-to-fluid Nusselt number for a multiparticle system. This correlation is based off the Reynolds number (Re_p) of the particle and the fluid Prandtl number and is valid for $Re_p > 50$.

Equation 14

(Ref. 5)

From the definition of the Nusselt number, the convection coefficient for the entire bed is found by

Equation 15

(Ref. 4)

This coefficient changes axially with temperature, as seen by the Nusselt number's dependence on the Prandtl number and (via the Reynolds number), density and viscosity. The properties were calculated from the section inlet temperature. For a given radial profile h_i will be constant.

For R_2 and R_3 all properties are known. The convection coefficient h_o for R_4 is easily found given the temperature of the ambient air. Since there is no active cooling implemented for the outside of the thruster, natural convection can be assumed. Incropera and DeWitt (Ref. 0) suggest the following correlation for the Rayleigh number $Ra_D \leq 10^{12}$:

Equation 16

The purpose of this thermal resistance network is to solve for the fluid temperature T_f . From basic heat transfer using the thermal resistance network,

Equation 17

Where

Equation 18

and q is the heat input to the system. The difficulty here is finding an expression for q . The heat is produced in this system by the reaction of hydrogen and oxygen in the presence of a catalyst. It is therefore assumed that the specific heat input of the system is equal to the heat of formation (h_f) of water vapor. This is usually given in terms of energy per mole. Converting to energy per mass and then multiplying by the mass flow rate gives power. However, not all of the hydrogen and oxygen are converted immediately. The percent converted, also known as the activity, is multiplied with the volume flow rate, the number of moles of water created per the volume being considered, and heat of formation to get the total heat produced:

—

Equation 19

In this case the percent is a mathematical quantity.

This is not the only relation that needs to be taken into account, however. There a change in the temperature profile with axial position as well as radial position. The thermal mass of the fluid can only hold so much heat. Using the relation

Equation 20

(Ref. 4)

Which, combining it with the equation above, gives

—

Equation 21

Recall that as the gas moves along the length of the catalyst bed the percent of hydrogen and oxygen will decrease and the percent of water vapor will increase. The mol term in the equation accounts for this, as does the density term.

D. Pressure Drop through the Catalyst Bed

The Ergun Equation is commonly used to calculate pressure drop through catalyst packed beds. It is written as follows:

— — — — —

Equation 22

(Ref. 0)

The pressure drops through the various portions of the catalyst bed are shown in the Table 2.

Table 2: Pressure Drops

Component	Pressure drop (psi)
Catalyst bed	50
Solenoid Valve	5
Tubing	5

Total	60
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Using this information it was determined that the inlet pressure for a chamber pressure of 100 psi needed to be about 150 psig.

V. Testing the Tri-gas Thruster

A. Design for the Test Rig

To test the thruster from a safe location, a gas system needed to be designed that would take the high-pressure Tri-gas and deliver it to the thruster at a set pressure for a pre-determined time. This was achieved using several high pressure components connected with $\frac{1}{2}$ " tubing. The 1500 psig Tri-gas is reduced using a dome loaded regulator, passed through a flow meter, and controlled using a solenoid valve. To ensure the system does not over pressurize an orifice was sized to a mass flow rate well below the capacity of the relief valve set at 500 psig. To actively cool the thruster after firing, a nitrogen purge system was put in place that uses 150 psig taken from a facility line. The purge line is controlled using a needle valve to set the flow and a solenoid valve to start and stop the purge. A diagram of the system that was used in the testing of the thruster is shown in Figure 9: Tri-gas Test System.

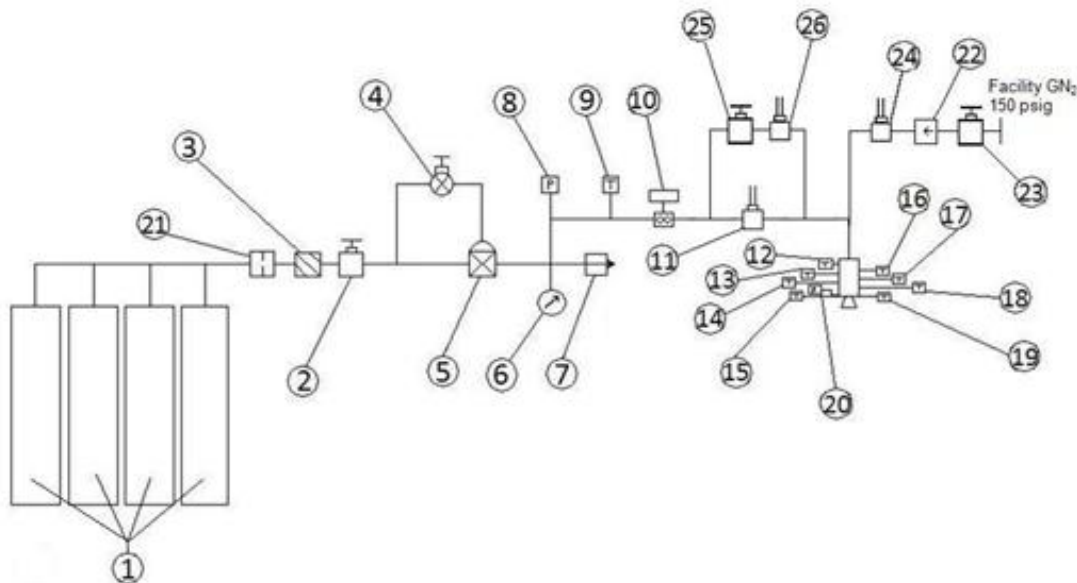


Figure 9: Tri-gas Test System

B. Sizing Lines and Components

Correctly sizing components is a critical step in designing a gas transfer system. Significant points of interest include tube length and diameter, C_v of valves, and flow limiting orifices.

Flow limiting orifices were incorporated within this design, permitting the relief valve to function correctly. Relief valves open when the pressure in the lines exceeds a pre-determined value. However, they can only expel up to a certain mass flow. The Agco-6 relief valve was chosen for this system due to its ability to open at 500psig and its availability within the in-house machine shop. According to the manufacturers, the relief valve will handle up to 2.805 lbm/s of Tri-gas.

A flow limiting orifice with a diameter of 0.018in was placed upstream of the relief valve. With an inlet pressure equal to that of the k-bottles and an outlet pressure of 500psig, the orifice allows a Tri-gas mass flow of 0.00677 lbm/s. The following equation from The Aerospace Fluid Component Designers' Handbook (equation 3.8.2.3a) determines this value.

$$\dot{m} = C_d A \sqrt{\frac{\rho (P_1 - P_2)}{1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma}{\gamma-1}}}}$$

Equation 23

(Ref.VII.6 6)

In this equation, P_1 is the pressure upstream of the orifice and P_2 is the downstream pressure.

Pressure drop caused by flow through valves must also be considered. Using the Tri-gas control solenoid as an example, the pressure drop caused by the component can be established using the above equation. The solenoid is stated by the manufacturer to have an equivalent orifice diameter of 0.395 in and a discharge coefficient of 0.6. Since pressure drop is maximized with a lower inlet pressure, P_1 was assumed to be 100 psig. Mass flow was taken from steady state thruster flow. Using these values, the above equation was solved for P_2 . The difference in inlet and outlet pressures led to the component pressure drop. For the solenoid, a pressure drop of 5 psi was predicted. An analysis of this type was also performed upon the filter and pressure regulator.

The length and diameter of tubing is an important parameter when designing a gas transfer system. Pressure drop through the line is directly related to the tube length. Two equations are used in tandem to determine pressure drop. The first equation determines the tube's friction factor:

$$\frac{f}{Re} = \frac{64}{Re} \quad \text{Equation 24}$$

Darcy's equation resolves the total pressure drop:

$$\Delta P = f \frac{L}{D} \frac{\rho v^2}{2} \quad \text{Equation 25}$$

(Ref. 0)

To establish a worst case pressure drop, the lowest achievable density was chosen to evaluate the above equations. Density is at a minimum when pressure is low and temperature is high. The pressure throughout the line was said to be 100 psia and at a temperature of 90°F (an average Alabama summer). With these conditions, a 92% nitrogen Tri-gas mixture has a density of $\rho = .45341 \text{ lbm/ft}^3$. (A Tri-gas mixture was chosen over pure nitrogen being that the mixture will have a lower density). The variables held constant throughout the analysis were:

$$\epsilon = 0.000005 \text{ (roughness of the tube)}, \quad \dot{m} = 0.0747 \text{ lbm/s}, \quad L = 10 \text{ ft (Estimated total pipe length)}$$

The above parameters provided a pressure drop of 78.1 psia with a tube diameter of 0.25 inch. However, it was noticed that pressure drop decreases significantly with an increase in diameter. This becomes apparent when looking at Darcy's equation; diameter appears in the denominator to the fifth power. When the tube diameter is increased to a half inch, the pressure drop becomes 2.12 psi. The group decided to design the thruster feed system with $d=1/2$ in tubing since it provides negligible pressure drop.

C. Procedure

The Tri-gas system was built so that 32 tests of approximately 30 seconds could be run. The parameters that would vary included catalyst type, catalyst bed length, start up temperature, and inlet pressure. For each test Tri-gas would be flown through the catalyst bed for 30 seconds then stopped. Then, nitrogen would be allowed to flow through the catalyst bed to lower the temperature in preparation for the next test's start temperature point.

Figure 10 show the first 14 tests planned. After test 6, 10 and 14 the thruster was removed from the stand and the catalyst bed length was changed. These first test were performed using the PuriStar R0-20/47PDE catalyst. This catalyst is comprised of 0.47 wt% Pd on an alumina sphere. These 14 tests were repeated for another catalyst, Engelhard C3788. It is composed of 0.4% Platinum and 0.1% Rhodium on an alumina sphere. Better reaction, leading to a higher peak temperature, was expected for this catalyst from work done at other locations.

Test No.	Run Time	Catalyst Type	Catalyst Bed Length	Chamber Pressure	Starting Temperature	Tridyne Mixture
1	30 sec	PuriStar R0-20/47PDE	2 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
2	30 sec	PuriStar R0-20/47PDE	2 in	100 psi	800 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
3	30 sec	PuriStar R0-20/47PDE	2 in	100 psi	650 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
4	30 sec	PuriStar R0-20/47PDE	2 in	100 psi	500 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
5	30 sec	PuriStar R0-20/47PDE	2 in	100 psi	350 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
6	30 sec	PuriStar R0-20/47PDE	2 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
7	30 sec	PuriStar R0-20/47PDE	1 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
8	30 sec	PuriStar R0-20/47PDE	1 in	100 psi	800 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
9	30 sec	PuriStar R0-20/47PDE	1 in	100 psi	500 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
10	30 sec	PuriStar R0-20/47PDE	1 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
11	30 sec	PuriStar R0-20/47PDE	3 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
12	30 sec	PuriStar R0-20/47PDE	3 in	100 psi	800 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
13	30 sec	PuriStar R0-20/47PDE	3 in	100 psi	500 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
14	30 sec	PuriStar R0-20/47PDE	3 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33

Figure 10: Tri-gas Thruster Testing Matrix for First Catalyst

Inlet pressure was varied in the last series of tests (Figure 11). This was done with the catalyst with the best expected performance and the longest catalyst bed, as the difference in pressure drop was hypothesized to be more apparent with this setup.

28	30 sec	Engelhard	3 in	125 psi	650 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
29	30 sec	Engelhard	3 in	150 psi	650 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
30	30 sec	Engelhard	3 in	175 psi	650 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
31	30 sec	Engelhard	3 in	200 psi	650 F	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33
32	30 sec	Engelhard	3 in	100 psi	Ambient	Nitrogen:92, Oxygen:2.67, Hydrogen:5.33

Figure 11: Tri-gas Thruster Testing Matrix for Inlet Pressure Variation

D. Data Collection

The plan initially was to have data collected by a DAQ trailer originally used to test oxygen methane thrusters. Due to time and instrument cooling issues, however, this plan eventually changed so the data was collected by the standard DAQ – a LabVIEW based system controlled in the main testing control room.

Data collected included pressure in the line and in the chamber, volume flow rate, and 8 temperatures along the length of the thruster in order to be able to calculate thrust based on the isentropic flow relations and to create a temperature profile along the catalyst bed length in an effort to characterize heat transfer and possibly catalyst activity.

Another data collection device was the FLIR infrared camera. The original idea was to use a fiber optic cable so the thruster could be used in infrared in real time; however, this was not achieved and video was eventually taken by connecting the camera by Firewire to a laptop computer and setting a timer. The infrared image was not calibrated, but provided a gross idea of heat transfer to the outside of the thruster.

E. Safety Concerns

Since safety is an essential element to experimentation, an additional hazards analysis was conducted for the Tri-gas Testing Procedure. Four primary dangers were identified and mitigated.

The initial concern was about personnel injury caused by overpressure or fragmentation from a thruster vessel rupture. To combat this risk, the thruster was designed to handle much higher pressures than anticipated. A considerable factor of safety was applied to the thruster chamber wall. A pressure relief valve was also incorporated upstream of the thruster to prevent it from experiencing high pressures. Procedural precautions were also implemented, such as placing a fragmentation barricade in front of the thruster and removing all personnel from the testing area.

The Tri-gas supply system was constructed in such a manner as to diminish the possibility of tube failure. Components were chosen in accordance with ASME requirements. The tubing lines were both proof and leaked tested after insulation. Pressure relief devices were installed to prevent pressures rising above 110% of the maximum working pressure.

Given that some of the thruster testing will be conducted in a vacuum chamber, the last safety measure was to prevent personnel and equipment damage from a vacuum chamber implosion. This scenario was avoided by confirming the vacuum chamber has been ASME certified and ensuring the modified flange does not alter vacuum chamber operational limits.

VI. Results

Testing was commenced on the first week of August of 2010 using the testing facilities described in section V. Tests were done varying the initial starting temperature, the length of the catalyst bed, and the inlet pressure of the Tri-Gas. Test success criteria were defined as any test that showed a significant increase in temperature that reached a steady state. A list of the tests complete can be seen in the tables below.

Table 3: Testing Completed on Tues 7/27/10
Gas Mixture One

Test Number	Catalyst	Cat. Length (in)	P at Nozzle (psig)	Start Temp Degrees F	Max Temp Degrees F	Success Criteria Met
1	Puristar	2	118	94	101	No
2	Puristar	2	Not Recovered	94	100	No
3	Engelhard	2	122	94	97	No
4	Engelhard	2	62	94	100	No

Table 4: Testing Completed on Mon 8/2/10
Gas Mixture One

Test Number	Catalyst	Cat. Length (in)	P at Nozzle (psig)	Start Temp Degrees F	Max Temp Degrees F	Success Criteria Met
5	Engelhard	2	134	82	763	Yes
6	Engelhard	2	135	344	765	Yes
7	Engelhard	2	137	442	764	Yes
8	Engelhard	2	140	499	762	Yes
9	Engelhard	2	78	552	782	Yes

Table 5: Testing Completed on Tues 8/3/10
Gas Mixture Two

Test Number	Catalyst	Cat. Length (in)	P at Nozzle (psig)	Start Temp Degrees F	Max Temp Degrees F	Success Criteria Met
10	Engelhard	2	128	97	734	Yes
11	Engelhard	3	115	115	126	No
12	Engelhard	3	125	134	836	Yes
13	Engelhard	3	118	120	553 (Peak)	No
14	Engelhard	3	122	121	398	Yes
15	Engelhard	3	79.7	144	411	Yes
16	Engelhard	3	118	116	139	No
17	Engelhard	2	128	121	386	Yes

Initial testing of the 2" and 3" catalyst beds looked promising. Each showed a quick increase in temperature with the 3" catalyst bed length having a larger final temperature than the 2". Soon after the 3" test took place, the system experienced an anomaly where the temperature of the thruster oscillated twice inside of 10 seconds with a range of about 200 degrees F. The data for this test was lost due to a problem with the data acquisition system. The anomaly was picked up and recorded by the thermal imaging camera. This test was conducted between test 12 and 13. Test 13 reacted in a similar manner but only experienced a peak of 553 deg F and then a drop in temperature, reaching a steady state near 400 deg F. Testing after this showed a significantly lower performance than that of previous tests. A test with the same physical catalyst used in the first test was tried last and reached a temperature 377 deg F less than that of the first successful test. The cause of this decrease in performance has not been determined, but has been theorized to be caused by a hydrogen leak in the system or a decrease of the reactivity of the catalyst. Percent

mixture sampling of the gas and testing with a newer catalyst is being planned to try and find an explanation for the occurrences.

The data that was recovered from the initial testing showed much promise for the feasibility of a Tri-Gas thruster design. The graph below plots the temperature increase of the 3” catalyst bed Tri-Gas thruster.

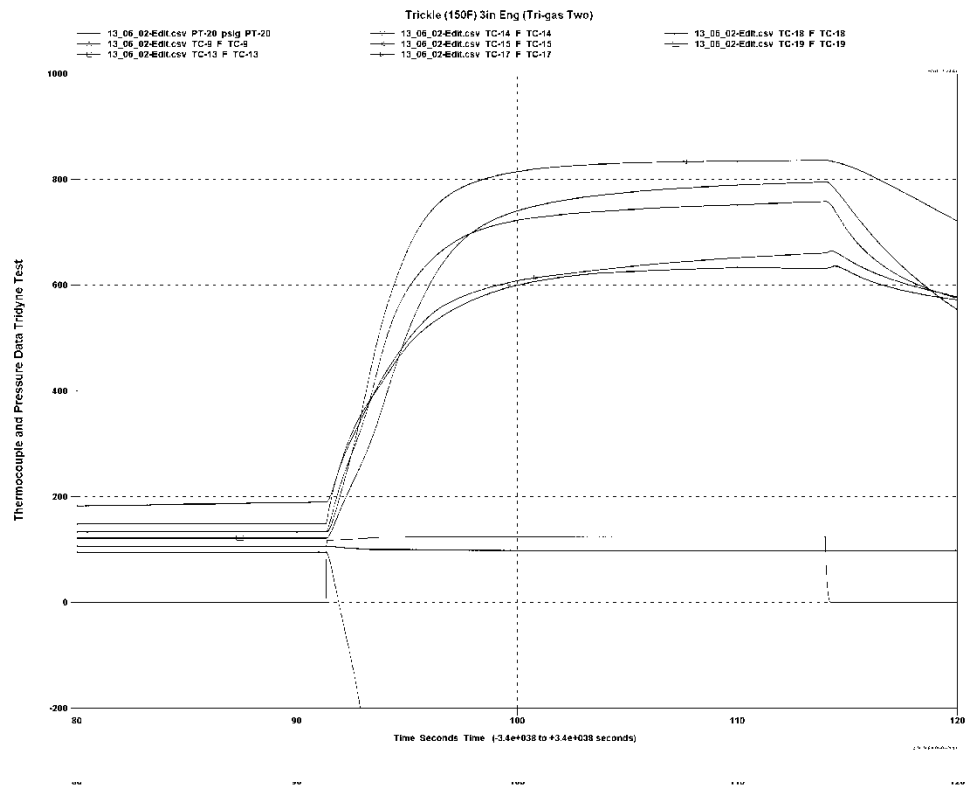


Figure 12: Three inch Engelhard test

Further data analysis was conducted on catalyst response time. The time for the exiting gas to reach within 5% of its steady state value was plotted against the average initial catalyst temperature. The same plots were created for P_c , mass flow rate, and inlet pressure. This data is necessary when evaluating Tri-gas thrusters for attitude control.

Table 6: Response time for selected variables

Average Initial Catalyst Temperature (°F)	Chamber Pressure Rise Time (s)	Inlet Pressure Rise Time (s)	Flow Rate Rise Time (s)	Exit Temperature Rise Time (s)
84.333	0.123	19.057	1.97	7.091
99.216	0.063	0.044	2.154	6.943
294.4	0.056	0.048	0.564	3.926
379.4	0.056	0.047	0.242	3.22
445.7	0.067	0.061	0.181	2.138

VII. Conclusion and Recommendations

While creating the Tri-gas there was a large amount of gas heating which led to difficulty in reaching a steady-state pressure after the bulk of the nitrogen was added. To mitigate this for later Tri-gas creation, water was used to cool the K-bottles and help the gas reach equilibrium faster.

There were also issues with catalyst poisoning. When the test was performed the first time the catalyst bed would not heat up. After baking the catalyst at 500°F for 2 hours the catalyst performed well for the tests immediately following the bake. If the gas is not catalyzing, baking the catalyst is recommended, especially if the catalyst has been stored for more than six months.

Further testing is recommended. Vacuum testing would be beneficial, though varying the chamber pressure and catalyst type would be informative. Another recommended test is to vary the Tri-gas component percentages to see how this impacts the thruster performance. For future testing it may also be interesting to incorporate a load cell in the test design to directly measure thrust.

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